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Numerical study of heat transfer in laminar and turbulent pipe flow with finite-size spherical particles

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ABSTRACT

Controlling heat and mass transfer in particulate suspensions has many applications in fuel combustion, food industry, pollution control and life science. We perform direct numerical simulations (DNS) to study the heat transfer within a suspension of neutrally buoyant, finite-size spherical particles in laminar and turbulent pipe flows, using the immersed boundary method (IBM) to account for the solid fluid interactions and a volume of fluid (VoF) method to resolve the temperature equation both inside and outside the particles. Particle volume fractions up to 40% are simulated for different pipe to particle diameter ratios. We show that a considerable heat transfer enhancement (up to 330%) can be achieved in the laminar regime by adding spherical particles. The heat transfer is observed to increase significantly as the pipe to particle diameter ratio decreases for the parameter range considered here. Larger particles are found to have a greater impact on the heat transfer enhancement than on the wall-drag increase. In the turbulent regime, however, only a transient increase in the heat transfer is observed and the process decelerates in time below the values in single-phase flows as high volume fractions of particles laminarize the core region of the pipe. A heat transfer enhancement, measured with respect to the single phase flow, is only achieved at volume fractions as low as 5% in a turbulent flow.

1. Introduction

Heat transfer in particulate suspensions is a rather common process in many industrial and environmental areas such as fuel combustion, food industry, pollution control and life science. Many industrial examples support the importance of heat transfer among the two phases (Zonta et al., 2008), thus, the understanding and the ability to predict the heat exchange in wall-bounded suspensions has been of interest among the researchers for many decades (Guha, 2008). Predicting the heat transfer requires a knowledge of how particles are distributed across a wall-bounded domain, how particles affect the flow field and finally how they affect the heat transfer within the suspension. Answering these questions is even more complicated in turbulent suspensions where the presence of finite-size particles modulates the turbulence structures (Naso and Prosperetti, 2010). Inertial effects at the particle scale, yet in laminar flows, are shown to induce modifications of the suspension microstructure and to create a local anisotropy responsible for shear-thickening (Kulkarni and Morris, 2008; Picano et al., 2013), thus to a change of the macroscopic suspension dynamics. Shear-thickening and particle migration towards regions of low shear has been documented in several studies in the literature for dense and dilute suspensions at low Reynolds numbers (Hampton et al., 1997; Brown and Jaeger, 2009; Yeo and Maxey, 2011; Guazzelli and Morris, 2011; Lashgari et al., 2017).

More in general, considering only the multiphase flow problem, Lashgari et al. (2014, 2016) documented the existence of three different regimes when changing the volume fraction ϕ of neutrally-buoyant spherical particles and the Reynolds number Re: a laminar-like regime at low Re and low to intermediate ϕ where the viscous stress dominates dissipation, a turbulent-like regime at high Reynolds number and low to intermediate ϕ where the turbulent Reynolds stress plays the main role in the momentum transfer across the channel and a third regime at higher ϕ, denoted as inertial shear-thickening, characterised by a significant enhancement of the wall shear stress due to the particle-induced stresses. Many studies have been dedicated in the recent years to the turbulence modulation in the presence of solid particles. A decrease of the critical Reynolds number for transition to turbulence is reported (Matas et al., 2003; Loisel et al., 2013; Yu et al., 2013; Lashgari et al., 2015) for semi-dilute suspensions of neutrally-buoyant spherical particles, whereas an enhancement of the turbulence activity is

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documented at low volume fraction (up to 10%) Picano et al. (2015); Costa et al. (2016). Conversely, turbulence attenuation is observed at higher volume fractions in suspensions of spherical particles (Picano et al., 2015) and for spheroidal particles also at lower volume fractions (Ardekani et al., 2017; Eshghinejadfard et al., 2017).

Heat transfer studies in the laminar regime date back to the experiments of Ahuja (1975) on sheared suspensions of polystyrene particles at finite particle Reynolds number ($Re_p > 1$); the author attributed the enhancement of heat transfer to a mechanism based on inertial effects in which the fluid around the particle is centrifuged by the particle rotation. These experiments revealed that, increasing the shear rate, particle concentration and particle size increases the thermal conductivity of the suspension. Shin and Lee (2000) experimentally studied the heat transfer of suspensions with low volume fractions (up to 10%) for different shear rates and particle sizes. They found that the heat transfer increases with shear rate and particle size, however, it saturates at large shear rates. Recently, Ardekani et al. (2018) numerically investigated the effect of particle inertia, volume fraction and thermal diffusivity ratio on the heat transfer in Couette flow suspensions of spherical particles. They revealed that inertia at the particle scale induces a non-linear increase of the heat transfer as a function of the volume fraction, unlike the case at vanishing inertia where heat transfer increases linearly (Metzger et al., 2013).

Heat transfer in non-isothermal particle-laden turbulent flows has been the subject of many studies in the recent years. Heat transfer between the two phases and the alteration of heat transfer efficiency are investigated in Namburu et al. (2009); Chang et al. (2011); Bu et al. (2013). Avila and Cervantes (1995), used a Lagrangian-stochastic-deterministic model (LSD) to show that high mass loadings of small particles increases the heat transfer rate, while at low mass loadings, the heat transfer rate decreases. Particle size effect is investigated in Zonta et al. (2008); Hetsroni et al. (2002), who show that larger particles increase the heat transfer coefficient more significantly than smaller ones by using a two-way coupling approximation. Kuerten et al. (2011) performed two-way coupling simulations of turbulent channel flow, showing an enhancement of the heat transfer and a small increase in the friction velocity in the presence of heavy inertial particles with high specific heat capacity. Liu et al. (2017) investigated the effect of the particle heat capacity by a point-particle model approximation and report that the heat transfer reduces when large inertial particles with low specific heat capacity are added to the flow.

Despite all the work on this subject, a complete study on the effect of particle size (for finite-size particles) and volume fraction on heat transfer in pipe flows is still missing in the literature. Here, we therefore perform direct numerical simulations of heat transfer in laminar and turbulent suspensions with neutrally buoyant, finite-size spherical particles in a cylindrical pipe up to 40% volume fractions. We hope that this study lays the ground for further parameter studies in this complex subject.

The paper is organised as follows. The governing equations, numerical methods and the flow geometry are introduced in Section 2, followed by the results of the numerical simulations in Section 3. Main conclusions and final remarks are drawn in Section 4.

2. Methodology

2.1. Governing equations

The flow of an incompressible fluid is described by the Navier–Stokes equations:

$$\rho_f\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu_f\nabla^2\mathbf{u} + \rho_f\mathbf{f}, \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0. \tag{2}$$

with $\mathbf{u}$ the fluid velocity, p the pressure, ρ_f the fluid density and μ_f the dynamic viscosity of the fluid. The buoyancy effects are neglected in this work since the Grashof number, Gr, is considered to be small compared to the Reynolds number, Re for the studied cases. The ratio, Gr/Re^2, can be used as a measure for the importance of natural convection (Incropera et al., 2007). In addition, small temperature differences are assumed so as to neglect density variations inside the fluid, thus allowing us to focus on the role of particle size and volume fraction. The additional term $\mathbf{f}$ is added on the right-hand-side of Eq. (1) to account for the presence of particles, modelled with the immersed boundary method (IBM). This IBM force is active in the immediate vicinity of a particle and at the pipe wall in the present implementation to impose the no-slip and no-penetration boundary conditions indirectly (see the description of the numerical algorithm below).

The motion of neutrally buoyant rigid spherical particles is described by the Newton-Euler Lagrangian equations,

$$\rho_p V_p \frac{\mathrm{d}\mathbf{U}_p}{\mathrm{d}t} = \oint_{\partial S_p} \boldsymbol{\tau}\cdot\mathbf{n}\,\mathrm{d}A - V_p\nabla p_e + \mathbf{F}_c, \tag{3}$$

$$\mathbf{I}_p \frac{\mathrm{d}\boldsymbol{\omega}_p}{\mathrm{d}t} = \oint_{\partial S_p} \mathbf{r}\times(\boldsymbol{\tau}\cdot\mathbf{n})\,\mathrm{d}A + \mathbf{T}_c, \tag{4}$$

with $\mathbf{U}_p$ and $\boldsymbol{\omega}_p$ the translational and the angular velocity of the particle. ρ_p, V_p and $\mathbf{I}_p$ are the particle mass density, volume and moment-of-inertia. The outward unit normal vector at the particle surface is denoted by $\mathbf{n}$ and $\mathbf{r}$ is the position vector from the particle center.

The integral of the stress tensor $\tau = -p\mathbf{I} + \mu_f(\nabla\mathbf{u} + \nabla\mathbf{u}^T)$ on the surface of particles accounts for the fluid-solid interactions, which are calculated by the IBM (see the description of the numerical algorithm below), while $V_p\nabla p_e$ in the expression above describes the external constant pressure gradient, used to drive the pipe flow at constant bulk velocity. $\mathbf{F}_c$ and $\mathbf{T}_c$ are the force and the torque, acting on the particles, due to the particle-particle (particle-wall) collisions.

The energy equation for incompressible flows can be simplified to:

$$\rho C_p\left[\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right] = \nabla\cdot(k\,\nabla T), \tag{5}$$

where C_p and k are the specific heat capacity and thermal conductivity, and T the temperature. We have considered the same ρC_p for the fluid and particles ($(\rho C_p)_p = (\rho C_p)_f$) in this study and thus Eq. (5) reduces to:

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \nabla\cdot(\alpha\,\nabla T), \tag{6}$$

where α is the thermal diffusivity, $\alpha = k/(\rho C_p)$.

Eq. (6) is resolved on every grid point in the computational domain, i.e. in the fluid and solid phases.

2.2. Numerical algorithm

Uhlmann (2005) developed a computationally efficient immersed boundary method (IBM) to fully resolve particle-laden flows. Breugem (2012) introduced improvements to this method, making it second order accurate in space while increasing the numerical stability of the method for mass density ratios (particle over fluid density ratio) near unity (see also Kempe and Fröhlich, 2012). Ardekani et al. (2018) coupled the IBM with a volume of fluid (VoF) approach (Hirt and Nichols, 1981; Ström and Sasic, 2013) to study the heat transfer in a suspension of rigid particles. In this numerical scheme, the IBM accounts for fluid-solid interactions and by computing the local volume fraction of the solid phase a VoF approach is employed to solve the temperature equation in the two phases where different thermal diffusivities can be considered. Details on the IBM, accounting for fluid-solid interactions are discussed in Breugem (2012) with several validations reported in Lambert et al. (2013); Picano et al. (2015); Lashgari et al. (2016); Ardekani et al. (2016). For clarity a short description of the IBM is given in this section, followed by the VoF method used for the heat transfer within the suspension.